

Recovery Gold from Waste Printed Circuit Boards by One-Step Combination Electrolysis and Chlorination Process

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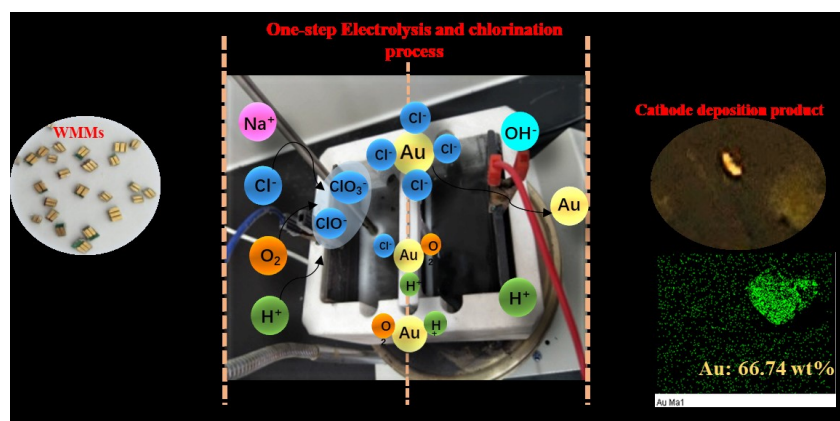
Citation: Yan Lu, Zizhen He, Bo Zeng, Jianbo Wang (2023) Recovery gold from Waste Printed Circuit Boards by One-step combination Electrolysis and Chlorination Process. *J Waste Resour Recycl* 5(1): 102

Received Date: June 10, 2023 **Accepted Date:** July 10, 2023 **Published Date:** July 27, 2023

Abstract

Simply by recycling the gold from in the ever-increasing mountains of used electronics, it is now possible to easily retrieve huge quantities of gold without having to do any digging into the earth at all. The majority of the currently available strategies for recycling gold from used electronics are mostly based on hydrometallurgy, which typically requires a series of recovery procedures that are both numerous and complex, including the use of hazardous chemical such as acids and alkalis. There is still a pressing demand for techniques that are both environmentally friendly and straightforward. We present here a method for directly recycling gold in a single reactor that does not involve the use of any acids or alkalis and is instead based on electrolysis and chlorination. The single component of the electrolyte in this system is sodium chloride. The reaction system of gold leaching in the anode region and simultaneously reduction in the cathode region in the combine electrolysis and chlorination system is established. The results showed that when the NaCl concentration was 3.8 mol/L, solid-liquid ratio was 5 g/L, current was 600A, 40oC, and 4h, 93.62wt% of gold being leached out and while 66.74% wt of gold was recycled from WPCBs, respectively. This research provides potentially significant ways for recovering gold from waste electronics in a quicker and more environmentally responsible way.

Keywords: Gold; Electrolysis; Chlorination; One-Step Recovery; Environmentally Friendly



Graphical Abstract

Introduction

Gold is commonly utilized in electronics, especially in bonding lines and electroplating layers of printed circuit boards, due to its high-quality electronic products [1]. With the development of technique, the electronic industry had consumed almost 3000 tons of gold in 2020 [2]. However, it is becoming more difficult to recover gold from mines, and mining cost becoming increasing [3]. Simultaneously, there is a constant stream of waste electronics production. In the recent years, annual global waste electronics production has averaged 93.5 million tons, with which waste printed circuit boards (WPCBs) containing 150 to 350 g/t of gold accounting for roughly 3-4% [4-5]. As a result, there is widespread agreement that repurposing electronic scrap as “Urban Minerals” for gold recovery is a good way to sustainably utilize resources, conserve minerals resources, and reduce pollution.

The mining of gold can be a very dirty business [3]. Due to the stable chemical characteristic of gold and particular difficulties associated with direct leaching processes, the commercial refining of this metal currently relies on strong oxides such as cyanide and aqua regia [6-7]. This procedure requires a huge amount of chemicals and is known for its detrimental influence on the environment and human health due to the enormous toxicity of cyanide and the corrosive nature of aqua regia [3]. Recently, various environmentally friendly processes for recycling gold have been developed. These processes involve the utilization of technologies such as leaching by chlorination, thiosulfate, thiourea, etc., followed by recovering through solvent extraction, ion exchange, etc [8-12]. Traditional hydrometallurgy offers the advantages of low energy consumption and easy control, nevertheless, the recovery stages are complicated, which can lead to enormous quantities of waste liquids and low recovery rates.

Metals can be separated and purified using electrolysis, which is seen as a promising technique because of its advantages of controllability, simplicity, and low equipment requirements, electrolysis is a promising technique for the separation and purification of metals [13]. At the same time, it is considered to be an environmentally and economically beneficial method [13]. It has been demonstrated that Chlorination techniques are effective, economical, and environmentally friendly for the recovering gold from waste electronic scrap [1]. The conventional chlorination processes, on the other hand, are plagued by the risks of chlorine leakage risks and inconvenient operation, both of which have precluded its widespread usage. Additionally, the process entailed the use of extremely corrosive acids and very hazardous chemical. What are some ways that the benefits of these two technologies can be applied to the innovation processing? Recently, various research has suggested using a procedure than combines electrolysis and chlorination to recover precious metals from WPCBs. When trying to extract gold from WPCBs in a separate reactor, Kim et al. [14] suggested using of chlorine as the oxidant agent and HCl. Both of these agents would be used in conjunction with each other. During this process, the electrically generated Cl_2 gas was linked to the anode compartment of HCl solution. As a result, 93% of gold was leached out. A slurry electrolysis technology was proposed by Wang et al. [1] for the extraction of gold from WPCBs in single reactor. Only NaCl was used as the electrolyte in the reaction system, and 98.96% of gold was successfully recovered. In its most basic form, this technology is a hybrid of electrolysis and a system based on NaCl, with chlorine ions serving as the oxidant agent.

However, these technologies concentrate more on leaching gold by electrolysis, the core task of gold recovery process is the absence of a reduction process. There is an urgent need for a method that is friendlier to the environment, shorter and continuous.

The direct recovery of gold from WPCBs in a single reactor without the use of any acids, alkalis and other potentially dangerous chemicals by just employing the NaCl system as an electrolytic medium is the primary objective of this research project. To our knowledge, this is the first time that a reaction system has been constructed that is capable of both leaching and reduction. During the electrolysis process, the factors that would affect the leaching efficiency of gold in the anode region and the recovery efficiency of gold in the cathode region are analyzed. The cathode product goes through an examination. This paper presents useful solutions for the recovery of precious in a manner that both more efficient and less damaging to the environment.

Experimental Section

Materials

In the course of this research, the WPCB was taken apart from discarded desktop computers that were given by a neighborhood organization that recycles electronic debris. After the gold-plated sections were first cut from the WPCB, they were subsequently sliced into smaller pieces to be used as the raw material. These pieces had a length of 1-3mm and a width of 1-3mm. The basic components of the raw material are detailed in Table 1.

element	Au	Cu	Ni	Al
Content (wt%)	0.22	20.82	1.45	1.44

Table 1: Compositions of main metals of the raw material [8]

All the tests were performed in a electrolyzer that was self-made and had the shape of a rectangle (length \times width \times height = 15 \times 7 \times 6 cm). A piece of acrylic fabric that had been added served to partition the electrolyzer into an anode zone and a cathode zone. As the anode and cathode, the graphite plate and the copper plate were put to use in this experiment, respectively. This electrolyzer was then placed in a magnetic stirrer (DF-101S, Lichen Technology, Shanghai, China) that had the capabilities of heating and stirring at a speed of 300 revolutions per minute at the anode cell. It is important to point out that the only component of the electrolyte in the reaction system is sodium chloride. A programmable direct current power supply was the source of the current (R-3005, Kingrang, China). A magnetic stirrer that maintained a consistent temperature was responsible for controlling both the temperature and the agitation of the reaction system (90-2A, Sedleys, China)

Experimental Procedures

Firstly, the electrolytic cell was filled with an aqueous solution of sodium chloride at the appropriate volume, and then the cell was heated to the required level. After that, the samples were transferred to the anode section of the apparatus. During this time, a source of DC constant current was used to provide a correct DC constant current that was maintained for a specified amount of time. As a result of the action of an electric current, the metals that was present in the samples was leached out in the anode region. Next, the leached-out metals were transported to the cathode region, where it was reduced to the form of particle that was in a suspended granulate state. The resultant particles that were deposited were filtered using 0.45m membrane filter while in a vacuum and then dried at 105°C for 2h. During the electrolysis tests, both the pH of the anode region and cathode region were measured and recorded.

The leaching rate and the recovery rate of metal were calculated by Eq (1) and Eq (2), respectively.

$$L = \frac{cXv}{m_0Xa} X100\%$$

$$R = \frac{m}{m_0Xa} X100\%$$

Where L is the leaching rate of metal, %; C is the concentration of metal in the leachate, g/L; V is the volume of the solution, 0.05 L; m₀ is the total mass of the sample, 5 g; and αA is the mass percent of metal in the sample. mis measured by an electronic balance with resolution 0.001g.

The Hydra Medusa is used to conduct an examination of the main chemical components present in the system. The Hydra and Medusa are two pieces of free software that complement each other: the Hydra and the database. The Hydra can pick the appropriate compounds, and the database finds any complexes or solids that may form, as well as the corresponding and the presence of species concentration are used by the Medusa programme to establish chemical equilibria. The values given to the Hydra-Medusa programme were chosen using the calculating procedures as shown in Eq (3) and (4). These values were determined from leaching tests.

$$[Cl^-]_{TOT} = C_{NaCl}XM_{Cl}X1000$$

$$[Au^{3+}]_{TOT} = C_{Au}XM_{Au}X1000$$

Where $[Cl^-]_{TOT}$ is the total concentration of Cl^- in the solution, mmol/L; C_{NaCl} is the NaCl concentration in the solution, g/L; M_{Cl} is the molar mass of Cl, 58 g/mol; $[Au^{3+}]_{TOT}$ is the total concentration of Au^{3+} in the solution, mmol/L; and M_{Au} is the molar mass of gold, 197 g/mol.

Chemical Analysis

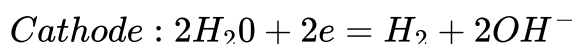
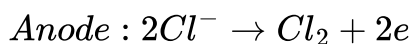
The compositions of the raw material are showed in Table 1, which were determined by inductively coupled plasma optical emission spectrometry (ICP-OES, Optima 8000, PerkinElmer, U.S.) after digesting with aqua regia. The concentration of Cl^- and OH^- in the solution was analyzed by Ion Chromatography (IC, IC-881, WanTong, Switzerland). The morphology of the cathode product was analyzed by Field-emission Scanning Electron Microscopy & Energy Dispersive Spectrometer (SEM MIRA 3 & EDS Aztec X-MaxN80, TESCAN Company, Czech Republic).

Results and Discuss

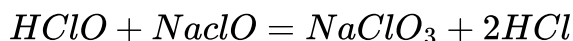
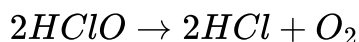
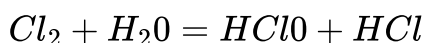
Electrochemical Behavior of NaCl Solution

The process of dissolving gold through electro-chlorination involves two simultaneous reactions: [1] electrolysis of NaCl solution to produce chlorine; and [2] the gold interacting with a sodium chloride solution that already contains chlorine, which causes the chlorine to become a complex chloride that is dissolved in the solution. In this study, NaCl was utilized as the electrolyte, graphite as the anode, and copper as the cathode. As a result of the fact that the discharge potential of the H^+ ion at the cathode region is -0.415V, which more positive than that of Na^+ ion (-2.718V), H^+ ions preferentially precipitated at the cathode. The discharge of OH^- and Cl^- ions are the primary activities that take place in the region surrounding the anode.

Because the OH^- ion has a discharge potential of 0.82V, and the Cl^- ion has a discharge potential of 1.33V, the Cl^- ions are preferentially precipitated at the anode. According to the above analysis, the main reactions of electrolytic NaCl on copper cathode and graphite anode are as shown in (4)-(6):



The electrode reaction process demonstrates that molecular chlorine, hydrogen, and alkali solution are the end results of electrolysis. The anolyte contains scattered and dissolved molecular chlorine produced during electrolysis. It can be seen from the electrode reaction process that the products obtained by electrolysis are molecular chlorine, hydrogen and alkali solutions. Molecular chlorine generated during electrolysis is dissolved and dispersed in the anolyte. The dissolved molecular chlorine and water in the sodium chloride solution establish the following equilibrium as shown in (4)-(5). The generation of hypochlorous acid in the solution, especially when there is hydrochloric acid in the solution, it does most change the ionic composition of solution near the anode, so it can not affect the electrolysis process. However, for the dissolution process of gold, the presence of hypochlorous acid has a great effect in the solution. Hypochlorous acid is easily decomposed into oxygen and hydrochloric acid under the action of light (reaction 6), the oxygen released is a strong oxidant in the process, simultaneously, neutralization of hypochlorous acid shifts the following equilibrium to the right (reaction 7), and prompting new chlorine to continue to dissolve. In the presence of hypochlorous acid, relatively high levels of hypochlorite in the electrolyte can lead to the production of chlorate. Chlorate can not only be formed in the presence of hypochlorous acid, but also when the electrolyte has sufficient alkalinity, hypochlorous acid will also spontaneously convert to chlorate, the reactions as shown in (7)-(12). The Electrochemical behavior of NaCl solution as shown in Figure 1.



Therefore, in the process of electrolysis of NaCl solution, the components that may exist in the electrolyte are: NaCl, NaClO, NaClO₃ and NaOH.

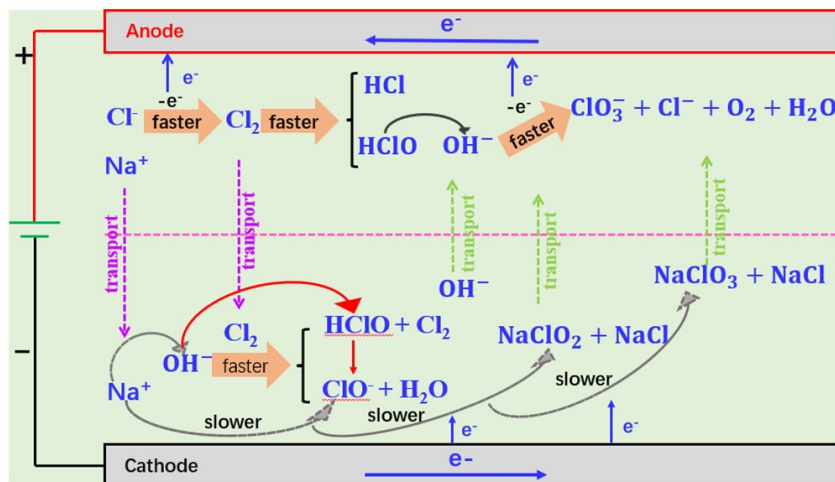
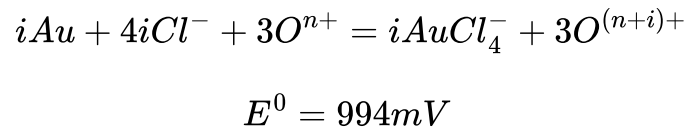


Figure 1: Electrochemical behavior of NaCl solution

Feasibility of Electro-Chlorination Recovery of Gold

Gold can get into the solution through the chlorination process when both of the following are accurate: (1) Cl⁻ is a ligand in the solution that binds to gold to make a stable complex of AuCl₄⁻; (2) the potential of the solution is higher than the standard potential of 994 mV for gold to bind to Cl⁻, as shown in reaction 13.

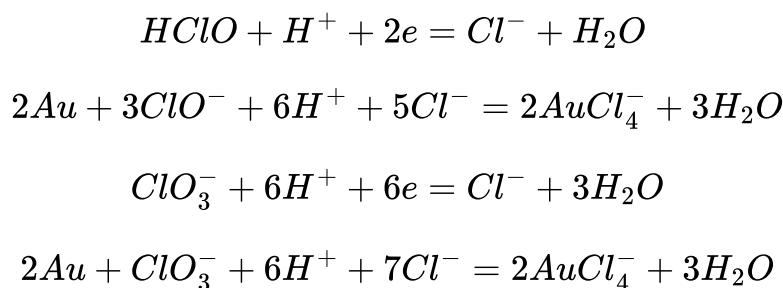


In the presence of oxidant, the electromotive force of gold leaching can be expressed as reaction [14]. φ_1^{θ} is the standard electrode potential of the oxidant. Under standard conditions, as long as the standard electrode potential of the oxidant is higher than 0.99 V, Au will be leached as trivalent gold chloride complex. When the standard electrode potential of the oxidant is higher than 1.12 V, Au will be leached in the form of monovalent gold chloride complex. As seen the reaction 14, increasing the concentration of complexing agent and oxidant, and continuously reduce the concentration of gold-chlorine complex in the leaching solution, the electromotive force of gold leaching reaction will increase, which is beneficial to gold leaching to improve the leaching rate.

$$E = \varphi_1^{\theta} - 0.99 + \frac{0.0592}{3i} \lg \frac{[Cl^{-}]^{4i} [O^{n+}]^3}{[AuCl_4^{-}]^i [O^{(n-1)+}]^3}$$

$$E = \varphi_1^{\theta} - 1.12 + \frac{0.0592}{3i} \lg \frac{[Cl^{-}]^{4i} [O^{n+}]^3}{[AuCl_4^{-}]^i [O^{(n-1)+}]^3}$$

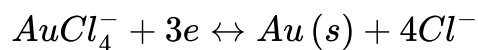
In this electro-chlorination leaching system, the oxidants are hypochlorous acid and perchloric acid. The electrode reaction participated by hypochlorous acid is shown in Eq (15), and its oxidation potential is $\varphi^{\theta}=1.49V$. The reaction of gold leaching with sodium hypochlorite as oxidant is shown in Eq (16). The ΔG_{2980} and $\lg K_{2980}$ of the reaction are -289.5kJ and 50.8, respectively, indicating that the reaction (16) proceeded spontaneously from left to right, and the reaction was very complete. Similarly, the electrode reaction involved in sodium chlorate is shown in Eq (17), its oxidation potential is $\varphi^{\theta}=1.45V$, and the reaction of sodium chlorate is used as an oxidant for gold leaching is shown in Eq (18). The ΔG_{2980} and $\lg K_{2980}$ of the reaction are -266.5kJ and 46.7, respectively, indicating the reaction (18) proceeded spontaneously from left to right, and the reaction was very complete.



Gold chloride complex ion can be reduced into gold particle when the potential of the cathode region is 0.93V, and then the reduction reaction can be realized. However, the electrochemical reduction reaction of gold deposition in the cathode phase is a heterogeneous reaction. The reaction takes place at the point where the cathode meets the gold leaching liquid phase. The reaction velocity is proportional to the surface area of the contact and the concentration of charged particles in the gold leaching solution. Furthermore, it is connected to the likelihood of effective collision between the ionized particles and the interface, as well as the cath-

ode characteristics and the electric potential. The entire response sequence is as follows: (1) The dissociation of $AuCl_4^-$ created at the anode is transferred to the cathode in the first stage, which is a mass transfer process; (2) the $AuCl_4^-$ ion in the cathode region is converted by the action of the electric field and collides with the cathode surface.

The dissociation of $AuCl_4^-$ in the gold leaching solution is very low, and the gold leaching solution can touch the electrode surface at a rate that is not equal to the $AuCl_4^-$. In actuality, the distance between the cathode and the anode is substantial, allowing the $AuCl_4^-$ ions in the flowing gold leaching solution to pass through easily. However, the cathode precipitates H_2 , preventing the $AuCl_4^-$ ions from colliding with the electrode [4]. Because the ions have very little probability of making contact with the cathode surface, the current created by them must be minimal; (3) When the altered $AuCl_4^-$ ions collide with the cathode surface in the third stage, they gain electrons and form gold and Cl^- ions. This stage is extremely reversible and can obtain electrons quickly, according to the Yap and Zhang, thus it is unlikely to be a control step in the electrocoagulation process [16-17]; (4) The reaction product Cl^- ions exit the cathode in the fourth phase, which cannot be the control step because the flow of gold leaching solution accelerates. Based on the comparison and analysis of the preceding four processes, it is possible to deduce that the electrodeposition of gold is determined by the effective collision between the cathode surface and the $AuCl_4^-$ ion, which is the primary cause of the reduction of the $AuCl_4^-$ ion to gold. In the reaction process, the discharge reaction of the gold chloride complex ion on the cathode plate as Eq (19).



Parameters Optimization

A suspension electrolysis system for direct recycling gold from WPCBs is established. The effects of NaCl concentration on the recovery performance of gold are investigated from 0.6 to 4.8 mol/L at 40 °C, 600 A, and a solid to liquid ration of 5g/L for 4h in Figure 2(a). The recovery rate of gold and the leaching rate of gold increase notably when NaCl concentration increases from 0.6 to 3.0 mol/L and increase slightly when NaCl concentrations increases to 3.8 mol/L. When the NaCl concentrations was 3.8 mol/L, the leaching rate and recovering rate of gold are all higher. Therefore, the optimal NaCl concentration for gold recovering is chosen as 3.8 mol/L in this study, because more leaching gold from WPCBs in the anode region is a precondition for more synthesis of gold in the cathode region. The leaching behaviors of gold at 1.6 mol/L and 3.8 mol/L NaCl concentrations were simulated by Hydra-Medusa software, respectively, as shown in Figure 3. It can be concluded that: (1) leaching behaviors of gold were identical 1.6 mol/L and 3.8 mol/L NaCl concentrations, indicating that the role of NaCl in the reaction system was only to provide the complexing reagent of Cl^- ; (2) under the condition of the electric field environment of the reaction system, $AuCl_x$, $AuCl_x(OH)_y$ - and $AuOH_x$ - were the complexes of gold in the solution in the range of approximately $pH < 2$, $pH < 8$ and $pH > 8$, respectively; (3) The production of O_2 , O_3 and H_2O_2 throughout the reaction indicates that gold passivation occurred concurrently with gold dissolution [15]. This phenomenon is consistent with the results of leaching gold with $NaClO_3$ - $NaCl$ - H_2SO_4 system [15].

The effects of temperature on the recovery performance of gold are investigated from 30 to 70 °C at 600 A with a NaCl concentration of 3.8 mol/L, and a solid to liquid ration of 5g/L for 4h in Figure 2(b). The recovery rate of gold and the leaching rate of gold increase dramatically when the temperature increase from 30 to 40 °C, and increase slightly when the temperature increase to 70 °C and actually peak at 40 °C. When the temperature is higher than 40 °C, NaCl begins to decompose quickly, which can provide more Cl^- for complexing with Au ion. However, high temperature can lead the Cl_2 overflow that reducing the concentration of chloride ions in the reaction system.

As shown in Figure 2(c), the effects of current in the recover performance of gold are investigated from 300 to 700 A at 40 °C with a NaCl concentration of 3.8 mol/L, and a solid to liquid ration of 5g/L for 4h in Figure 1(c). With the increase of the current from 300 to 500A, the recovery rate of gold increase from 37.21% to 61.3%, and the leaching rate of gold increase from 52.10 to 76.87%. When the current increase to 700A, the leaching rate of gold increase to 82.4%. In contrast, the recovery rate of gold decreases to 68.93%. With a certain range, an increase in current contributes to promote the reaction. However, excessive current hinders the re-

action.

The effect of holding time on the recovering performance of gold are investigate from 2 to 6h at 40 oC,600A with a NaCl concentration of 3.8 mol/L, and a solid to liquid ration of 5g/L in Figure 1(d). The recovery rate of gold and the leaching rate of gold increase dramatically with the holding time increasing from 2 to 4 h and all peak in 4h. Then a plateau is observed in the range from 4 to 6h, which means that the reaction has been completed under the given conditions.

The effects of NaCl concentration, temperature, current and holding time on the leaching performance of Copper are also conducted in Figure 2. With the increase of the conditions, the leaching rate of Copper is increase. Particularly, the concentration of NaCl has a significant impact on the copper leaching process. The oxidation potential of copper in the chlorinated system is 340mV, which is lower than gold. However, in the intact circuit board, the gold is deposited on a copper-containing substrate, allowing it to bind preferentially to the complex ions. Under different conditions, the copper leaching rate is between 28%-47%. Copper leaching affects gold purity during the gold recovery process using an electric chlorination system. We have assumed that modifying the filtering membrane separating the cathode and the anode might improve the purity of recovered gold, but the appropriate literature has not been discovered.

The pH values and the potential values in both the anode region and cathode region, as well as the complex species of gold under the optimal condition of 3.8 mol/L NaCl concentration, 600A/m², 40oC, and 4 h, were determined, which can better comprehend the process of the technology, as depicted in Figure 4. During the electrolysis process, the pH value decreased simultaneously (Fig.4a) and the potential increased considerably in the anode region (Figure 4b), which extremely promoted the dissolution of gold; while the potential drops in the cathode region promoted the reduction of gold. It can be seen that with the increase of, the concentration of Au (OH) fell as Cl⁻ concentration grew, whereas AuCl₄⁻ concentration increased, and AuCl₄⁻ reached its maximum at about 1.1M Cl⁻. Consequently, when the concentration of Cl⁻ increased, the change of the electroactive material reduced, resulting in less diffusion, and a lower peak current at the cathode.

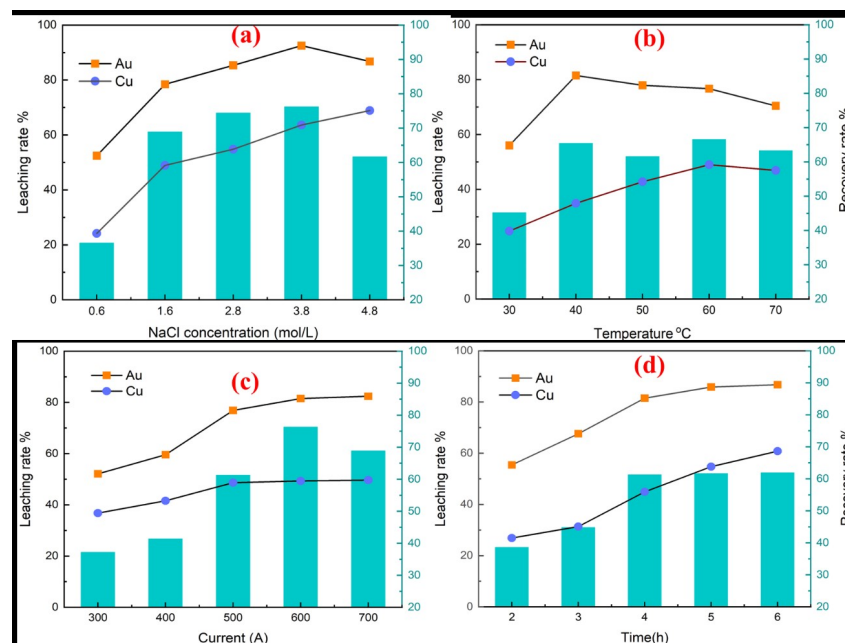


Figure 2: Effects of on leaching rates of gold and Cu, and recovery rate of gold, respectively: (a) NaCl concentration, at 40 oC, 600 A, and a solid to liquid ration of 5g/L for 4h; (b) temperature, at 600 A with a NaCl concentration of 3.8 mol/L, and a solid to liquid ration of 5g/L for 4h; (c) current, , at 40 oC with a NaCl concentration of 3.8 mol/L, and a solid to liquid ration of 5g/L for 4h; (d) holding time, at 40 oC, 600 A, and a solid to liquid ration of 5g/L with a NaCl concentration of 3.8 mol/L.

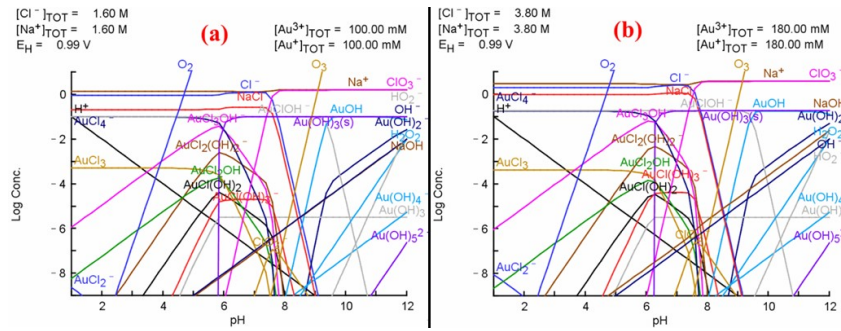


Figure 3: Gold leaching behavior simulated by Hydra-Medusa software at different NaCl concentration: (a) 1.6 mol/L, (b) 3.8 mol/L.

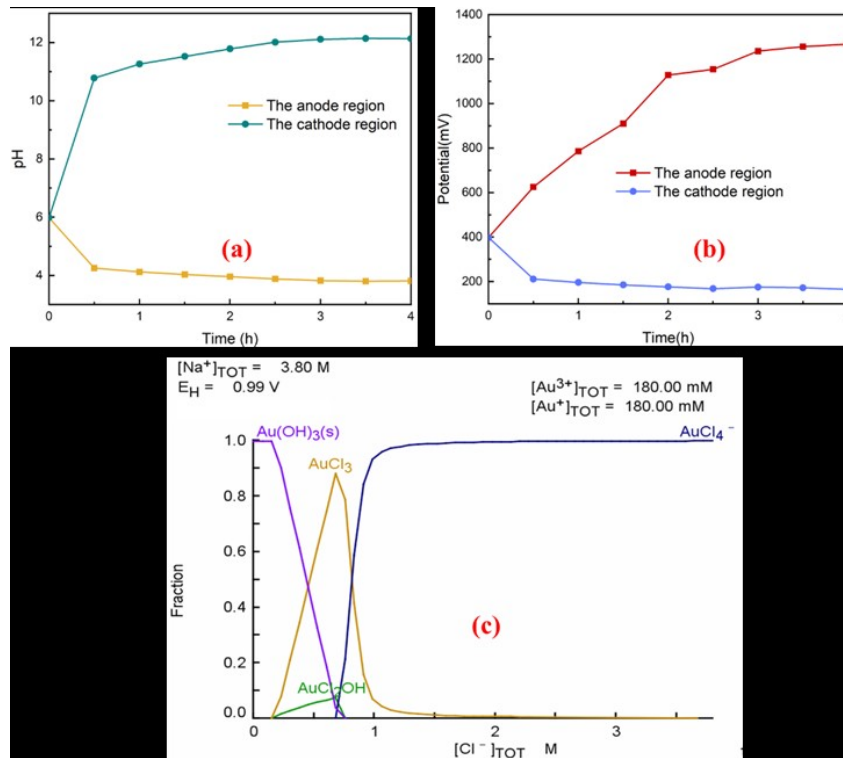


Figure 4: Changes in pH (a) and potential (b) in the anode region and cathode region, (c) Complex species of gold in the different Cl⁻ concentration, under the optimal condition of 3.8 mol/L NaCl concentration, 600A/m², 40oC, and 4 h.

Gold Recycling Test

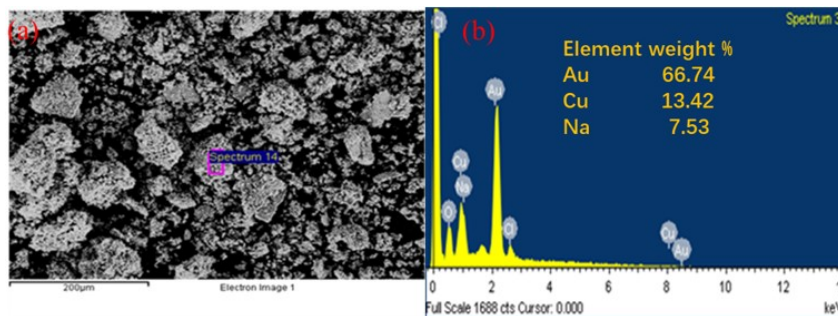


Figure 5: Flowchart of recovering gold from WPCBs

Figure 6: (a) scanning electron microscopy and (b) energy spectrum of cathodic deposition product from WPCBs recovery test.

In light of the findings presented above, it can be deduced that the concentration of NaCl was 3.8 mol/L, the current of 600A, the temperature of 40 oC, the solid to liquid ration of 5 g/L, the holding time of 4h, the tests will result in the highest possible recovery rate of gold, as shown in Fig.5. According to the findings, the material that is deposited as a result of cathodic oxidation is gold (Fig.6). The rate at which gold was leached from WPCBs was 93.62wt%, whereas the recovery rate for gold was 66.74 wt%.

Conclusion

In this paper, the recycling of gold from WPCBs was investigated. For the purpose of directly recycling gold, an electrochemical reaction system is capable of dissolution and recovery in a single has been established. The 3.8 mol/L NaCl concentration, 5 g/L solid to liquid ration, 600A of current, 40oC, and 4h were the optimized parameters of the process that were determined by experiment. The conditions described above resulted in 93.62wt% of gold being leached out and while 66.74% wt of gold was recycled from WPCBs.

The electro-chlorination technique is employed to extract gold from gold containing waste. The entire process is performed in a single electrolyte, which has the following benefits: (1) minimal size; (2) no other chemical reagents are required; (3) simple and low-cost process; (4) good selectivity and metal deposition rate; (5) the leached waste liquid may be collected and reused. The effect of metal deposition can be enhanced by improving the electrode material of an electrolytic cell as new materials are developed. At the same time, electro-chlorination technique has a number of weaknesses that require further investigation. The important aspects are: (1) parameter improvement and electrolytic cell structure optimization; (2) it is still unable to deal with low grade waste; and (3) how to enhance current efficiency and reduce waste liquid pollution to accomplish the effect of energy saving, high efficiency, and recycling. Although electro-chlorination technique is not optimal at the moment, with continued scientific research, it will be a promising gold recovery process. In subsequent works, with a particular focus on the enhancement of gold recovery efficiency and the separation of contaminants will be carried out in an effort to gain a deeper comprehension of this technology.

Highlights

- Electrolysis technology with NaCl system to directly recover gold is established.
- The factors that would affect leaching and recovery efficiency of gold are examined.
- The complex of gold were AuCl_x , $\text{AuCl}_x(\text{OH})_y^-$ and AuOH_x^- in the leaching process
- The total recovery rate of gold reached 66.74 wt%.

Declaration of Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRedit Authorship Contribution Statement

Yan Lu: Conceptualization, Investigation, Methodology, Formal analysis, Resources, Writing-original draft, Writing-review & editing, Validation.

Zizhen He: Conceptualization, Investigation, Methodology, Formal analysis, Visualization.

Bo Zeng: Writing-review & editing, Formal analysis, Validation.

Jianbo Wang: Project administration, Supervision, Conceptualization, Funding acquisition, Resources, Validation.

Acknowledgement

This work was supported by the National Natural Science Foundation of China (52000152). The authors are grateful to the reviewers who help them improve the paper by many pertinent comments and suggestions.

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